Beam Loading in the HPRF Cavity

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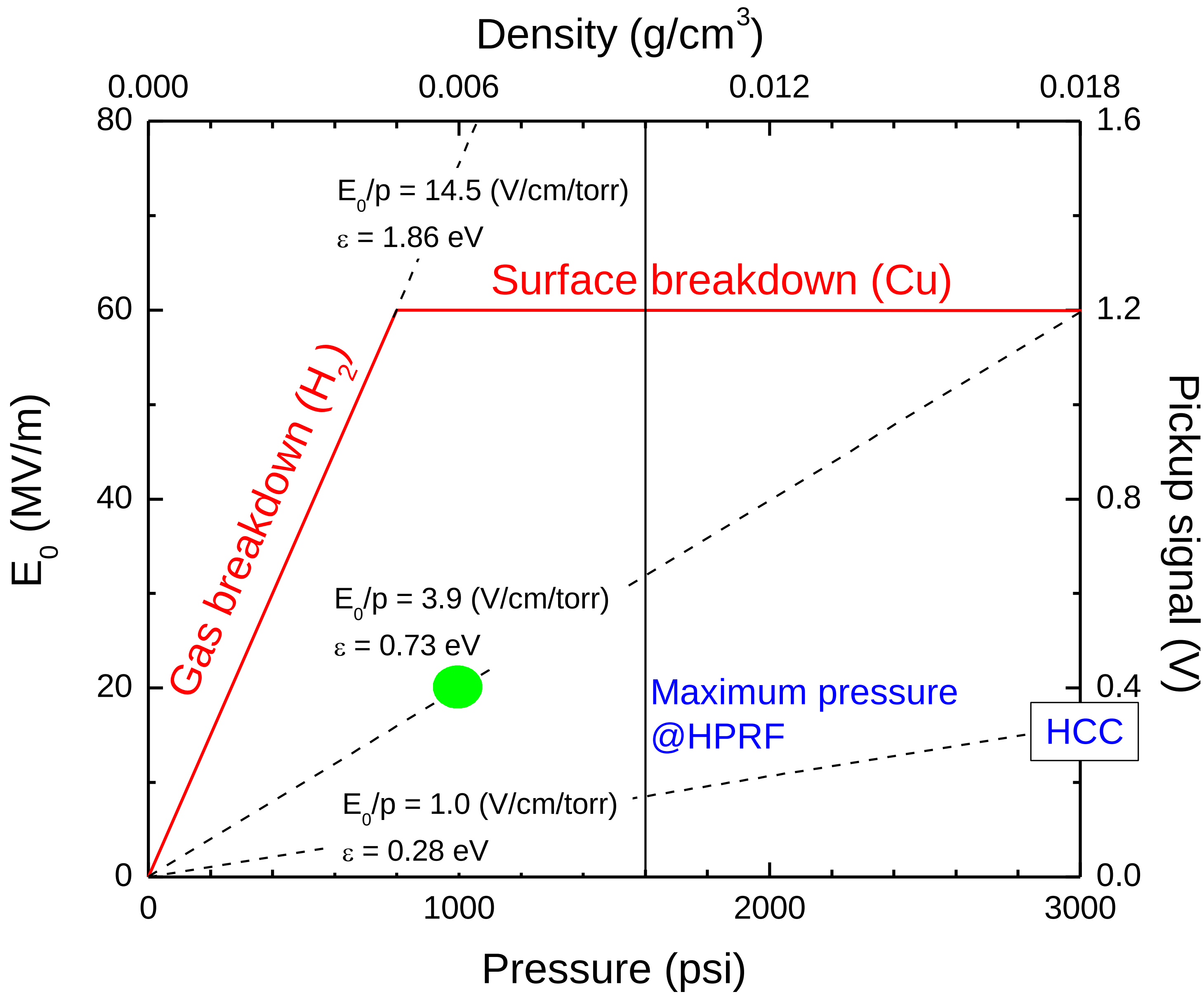
Moses Chung

APC, Fermilab

with

Alvin Tollestrup, Andreas Jansson, Katsuya Yonehara



Density (g/cm^3)
0.000
0.006
0.012
0.018
80
60
40
20
0
1.6
1.2
0.8
0.4
0.0
E_0/p = 14.5 (V/cm/torr)
ε = 1.86 eV
Surface breakdown (Cu)
Gas breakdown (H_2)
E_0/p = 3.9 (V/cm/torr)
ε = 0.73 eV
Maximum pressure
@HPRF
HCC
E_0/p = 1.0 (V/cm/torr)
ε = 0.28 eV
E_0 (MV/m)
Pickup signal (V)
0
1000
2000
3000
Pressure (psi)

Without beam

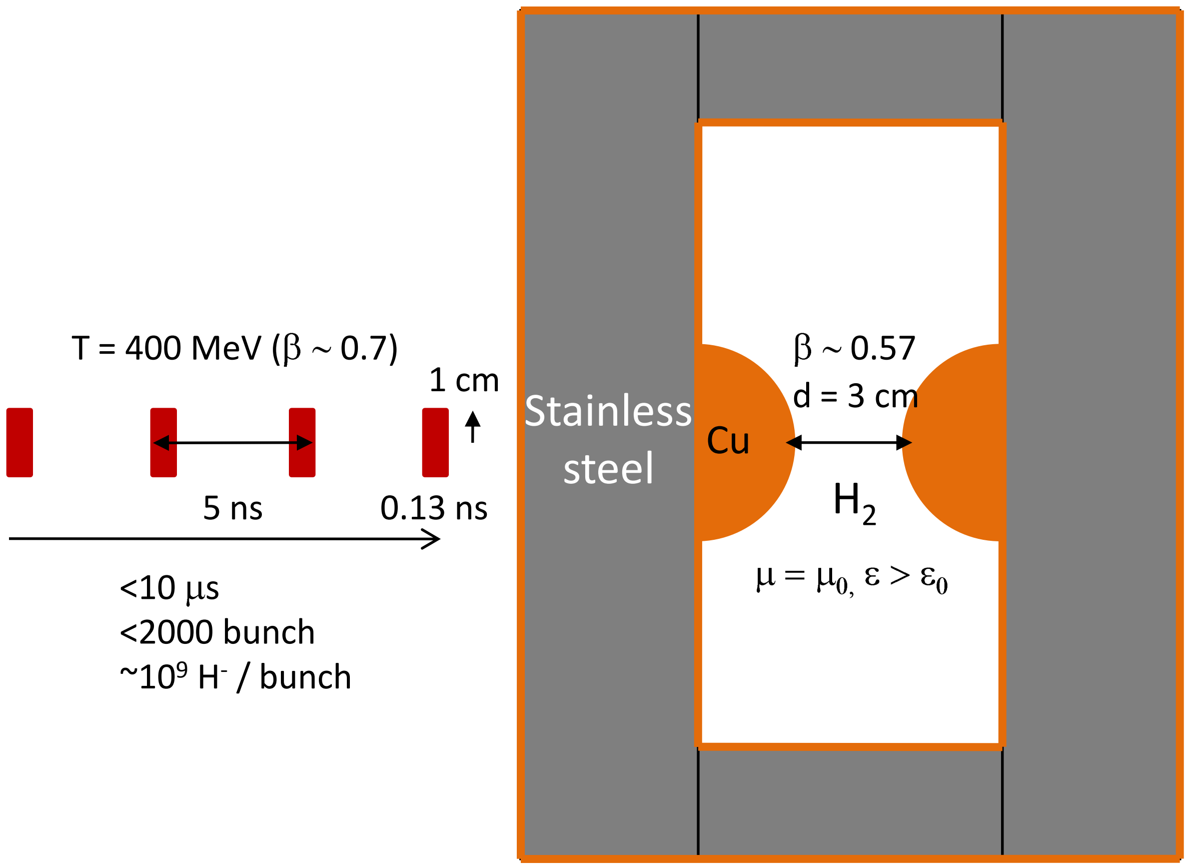
Surface-emitted electrons
(K. Yonehara)

Beam with Material

Secondary electrons
~ 2/1000 proton
(I. Rakhno)

Beam in the Cavity

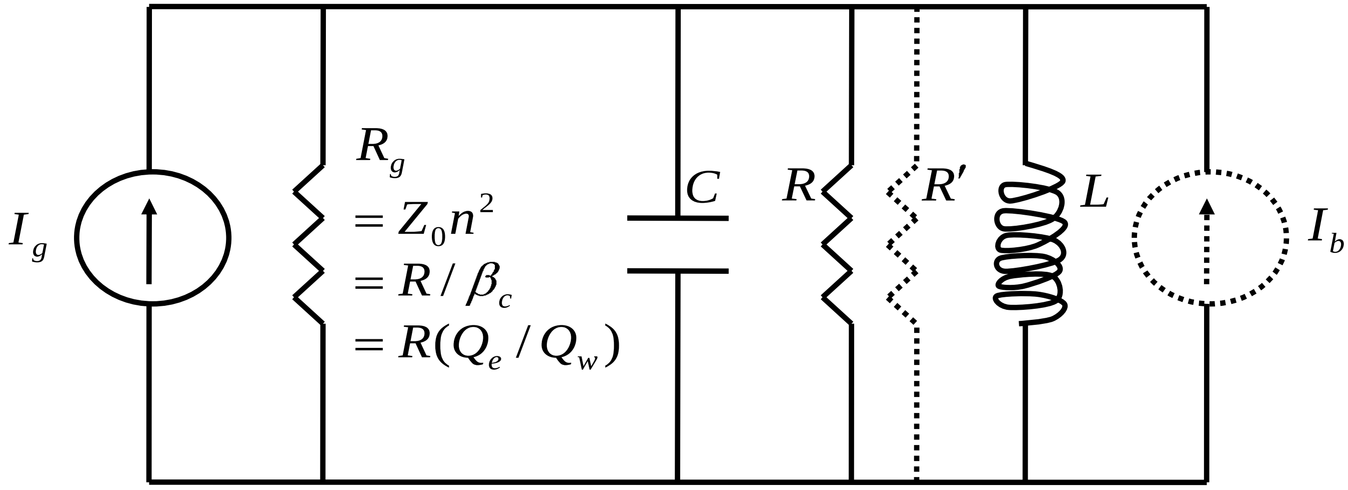
Beam-induced electrons
~ 1000/proton
(A. Tollestrup)



Equivalent Circuit Model

$$V_c(t) = V_g(t) + V_b(t) = V_F(t) + V_R(t)$$

Matched generator



$$\omega_0 = 1/\sqrt{LC}, \;\; Q_w = \omega_0 RC$$

$$\boxed{\left\{ \frac{d^2}{dt^2} + \omega_0 \left(\frac{1}{Q_L} + \Delta\left(\frac{1}{Q}\right) \right) + \omega_0^2 \right\} V_c = 2\frac{\omega_0}{Q_e}\frac{dV_F}{dt} - \frac{\omega_0}{2}\left[\frac{R}{Q}\right]\frac{dI_b}{dt}}$$

Additional damping term by beam-induced electrons (as plasma people do)

Additional driving term by beam itself (as RF people do)

Model Equation

In the slowly-varying envelope approximation: $\left|d\tilde{V}_c / dt\right| << \left|\omega \tilde{V}_c\right|$

beam-induced electrons

beam itself

$$\boxed{\frac{d\tilde{V}_c}{d\tau} + (1 - j\tan\psi + \gamma)\tilde{V}_c = \frac{1}{2} Q_L \left[\frac{R}{Q}\right](\tilde{I}_g - \tilde{I}_b)}$$

$$V_c(t) = \mathrm{Re}(\tilde{V}_c(t) e^{j\omega t}), \ \left|\tilde{V}_c\right| \approx E_0 T d, \ T = \text{transit-time factor} \approx 0.96$$

$$\tau = \frac{t}{T_f}, \ T_f = 2Q_L / \omega_0 = \text{filling time}$$

$$\tan\psi = Q_L \left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right)$$

$$\gamma = Q_L \Delta \left(\frac{1}{Q}\right)$$

$$\left[\frac{R}{Q}\right] = \frac{\left|\tilde{V}_c\right|^2}{\omega_0 U} \approx 377 \times T^2 \frac{d}{R_w} \sim 129\,\Omega$$

1. Beam Itself

Beam Current

$$I_{DC} = \frac{q_b}{T_b} = \frac{Ne}{k(2\pi/\omega)} \approx \frac{10^9(1.6\times10^{-19})}{4/(805\,\text{MHz})} \approx 32\ \text{mA}$$

For t_b(bunch length $\approx$ 0.13ns) $<<$ T_b(bunch spacing $\approx$ 5ns)

$$I_b(t) = q_b \sum_{m=-\infty}^{\infty} \delta(t - mT_b) = \frac{2q_b}{T_b}\,\mathrm{Re}\left[\frac{1}{2} + \sum_{n=1}^{\infty} e^{j\omega t\left(\frac{n}{k}\right)}\right]$$

For a given harmonics

$$\tilde{I}_b = \frac{2q_b}{T_b} = 2I_{DC}$$

Beam-induced voltage in steady state with γ=0

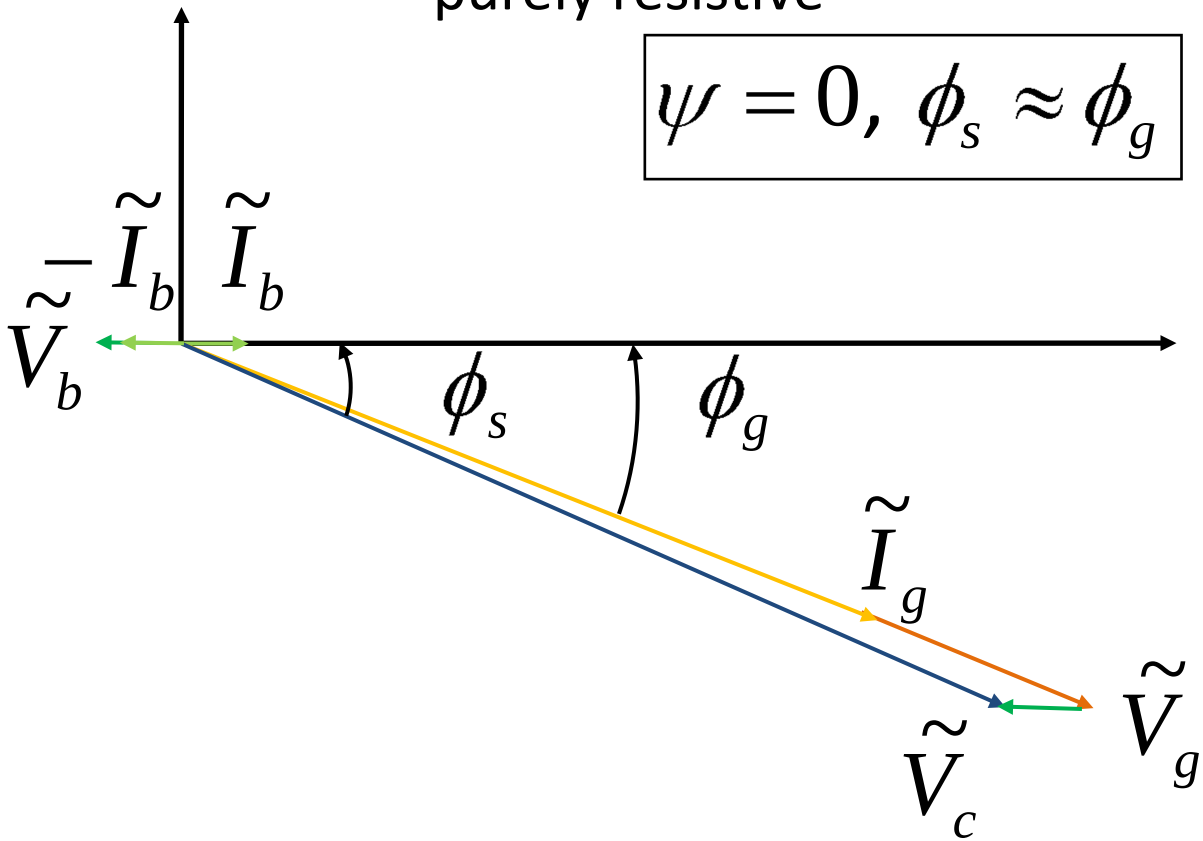
$$\tilde{V}_b = -\cos\psi e^{j\psi}\frac{1}{2}Q_L\left[\frac{R}{Q}\right]\tilde{I}_b = -Z_{||}(\omega)\tilde{I}_b$$

$$\boxed{\left|\tilde{V}_b\right| \sim 25\ \text{kV} << \left|\tilde{V}_c\right| \approx 20\text{MV/m}\times 3\,\text{cm}\times 0.96 \approx 580\ \text{kV}}$$

If V_b negligible…

The cavity appears to the generator purely resistive

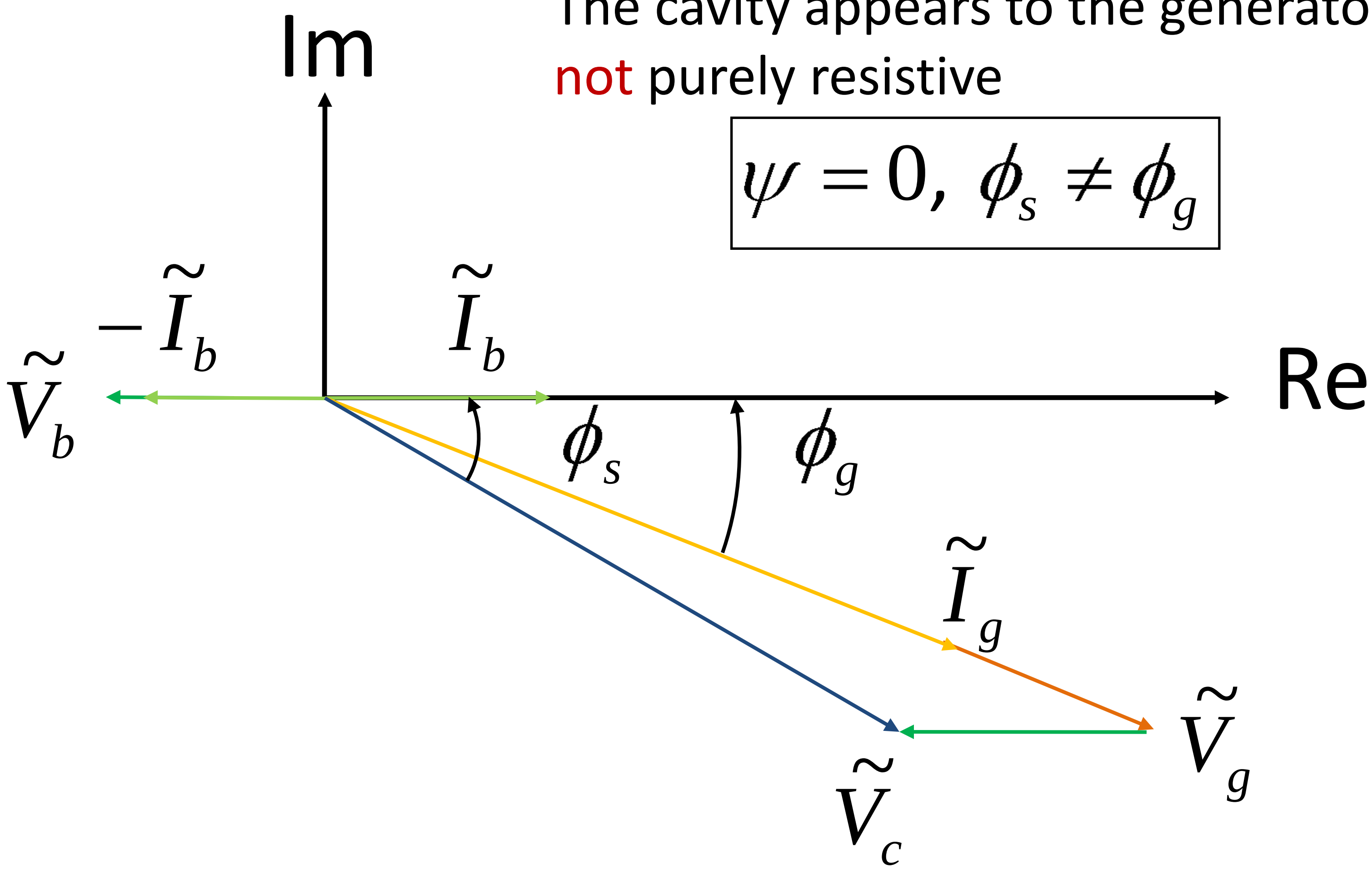
$$\boxed{\psi = 0,\ \phi_s \approx \phi_g}$$



If V_b not negligible...

The cavity appears to the generator not purely resistive

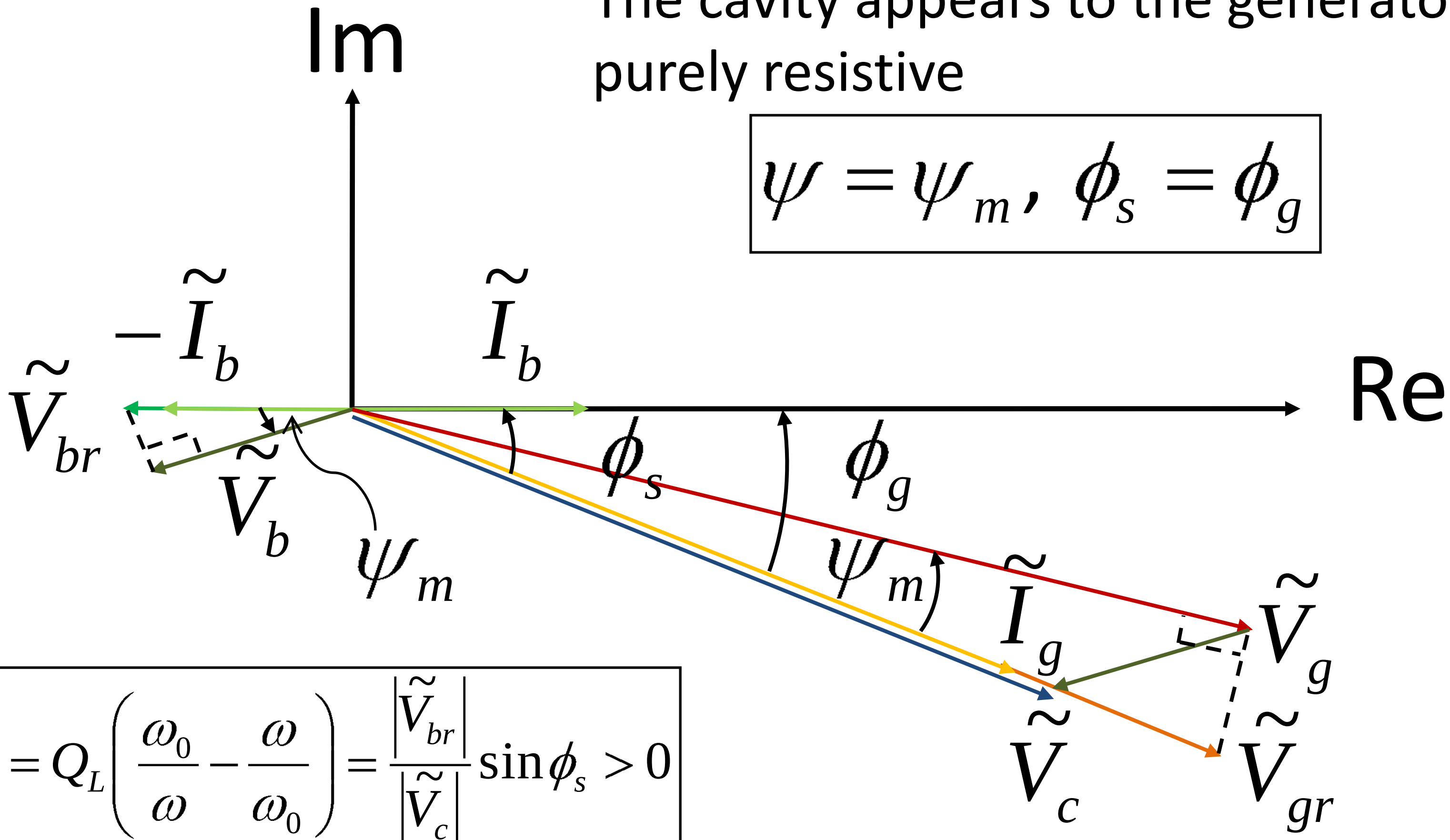
$$\boxed{\psi = 0,\ \phi_s \neq \phi_g}$$



…detuning is required

The cavity appears to the generator purely resistive

$$\boxed{\psi = \psi_m,\ \phi_s = \phi_g}$$



$$\boxed{\tan\psi_m = Q_L\left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right) = \frac{|\tilde{V}_{br}|}{|\tilde{V}_c|}\sin\phi_s > 0}$$

In fact, coupling coefficient needs to be adjusted as well to further minimize reflection

Operation Consideration

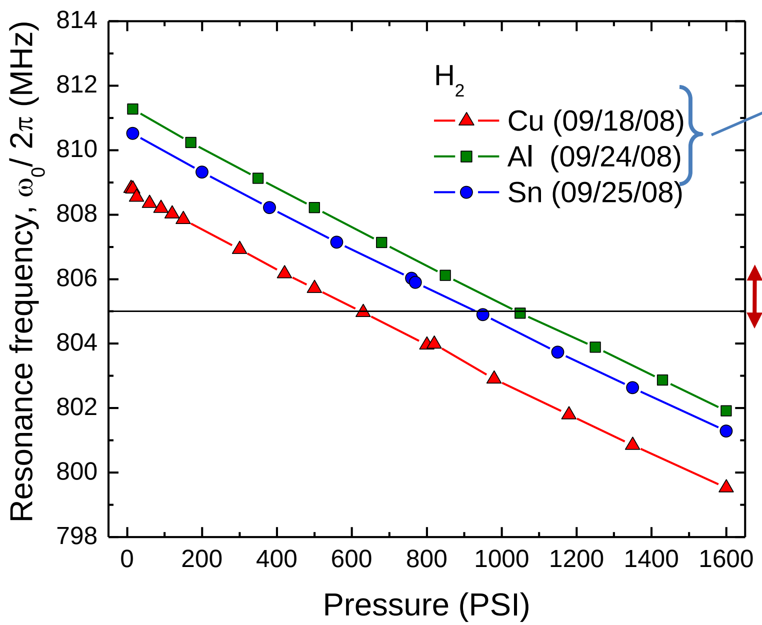
The required detuning is small

Last digit of the
RF waveform generator

$$f_0 - f \approx \frac{f_0}{2Q_L}\tan\psi_m \sim 1.4\,\text{kHz} \ll \frac{f_0}{2Q_L} \sim 67\,\text{kHz}(\text{for } 3\text{dB})$$

If driving frequency (ω) is phase-locked to the Linac for constant synchronous phase, it is important to check available pressure range.

If driving frequency (ω) is not phase-locked to the Linac, triggering and delay should be set properly so the RF is on when beam passes through the cavity



Shift not from material properties
but from the geometry of the specific electrode

$f = \omega/2\pi = 805$ MHz
(Driving frequency)

Install remote tuner next time?

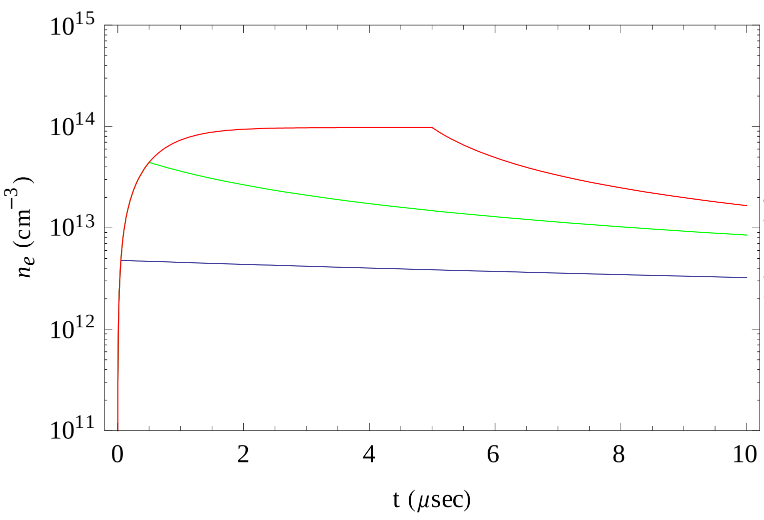
2. Beam-induced Electrons

Electron Generation

Proton beam produces electrons
by proton-impact ionization + ionization by secondary electrons

$$\boxed{\frac{\Delta n_e}{1\ \text{proton}} \approx \frac{\rho(dE/dx)\Delta s}{W_i(\approx 35\ \text{eV})} \times \frac{1}{(\pi r_b^2 \Delta s)}}$$

Most (or some) electrons will be thermalized quickly (energy equilibration is much faster than density evolution) by elastic + inelastic collisions,
and drifting with RF until annihilated (recombination + attachment + diffusion)



$$\frac{dn_e}{dt} \approx S - \beta_r(T_e)n_e^2 \underbrace{- k_a(T_e,T_g)n_e n_g - \frac{D(T_e)}{\Lambda^2}n_e}$$

Estimated to be small
T_e < 1 eV, T_g ~ 300 K
→Need more simulation
→Oopic, LSP(Voss)

Perturbation from Electrons

$$\sigma_{DC} \propto \frac{n_e}{\nu_m} \propto \frac{\rho}{p}$$

Need nonlinear correction for low E_0/p
For $E_0/p \sim 1.0$, $\chi \sim 3$
For $E_0/p \sim 3.9$, $\chi \sim 1.5$

$$\boxed{\Delta\left(\frac{1}{Q}\right) = \frac{\int_V \frac{1}{2}\sigma_{DC}(r)E_0^2(r)dV}{\omega_0 \int_V \frac{1}{2}\varepsilon_0 E_0^2(r)dV} \rightarrow \chi(E_0/p)\Delta\left(\frac{1}{Q}\right)}$$

Independent of p

$$\boxed{\Delta f = \frac{f_0}{2}\left(\frac{\omega_0}{\nu_m}\right) \times \Delta\left(\frac{1}{Q}\right) << 1\,\text{kHz}}$$

Purely resistive:
no significant changes in reactive component
(Ue = Um)

Damping coefficient

$$\boxed{\gamma = Q_L \Delta\left(\frac{1}{Q}\right) = \frac{P_{Ohmic}}{P_{ext} + P_{wall}}}$$

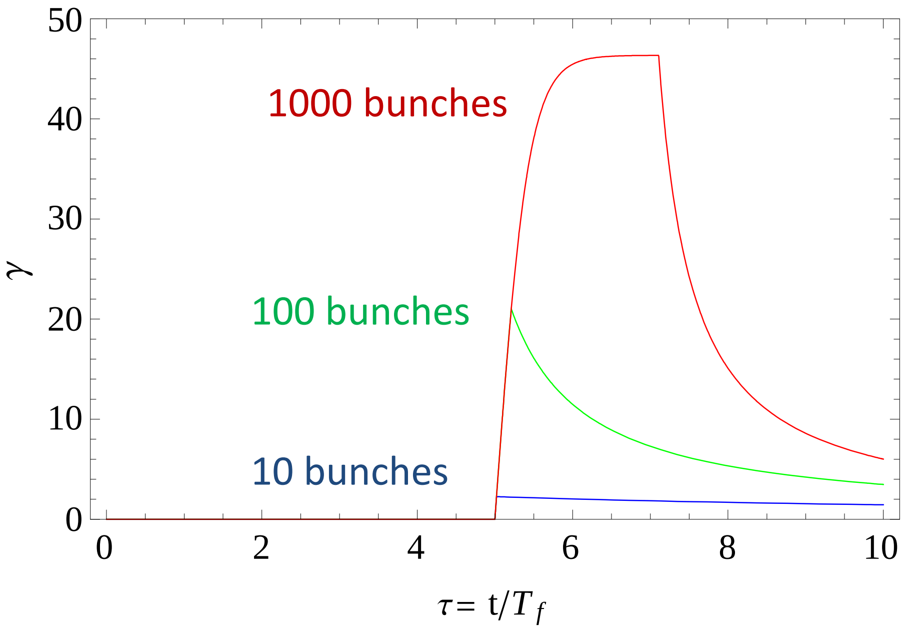
Ohmic heating of hydrogen gas

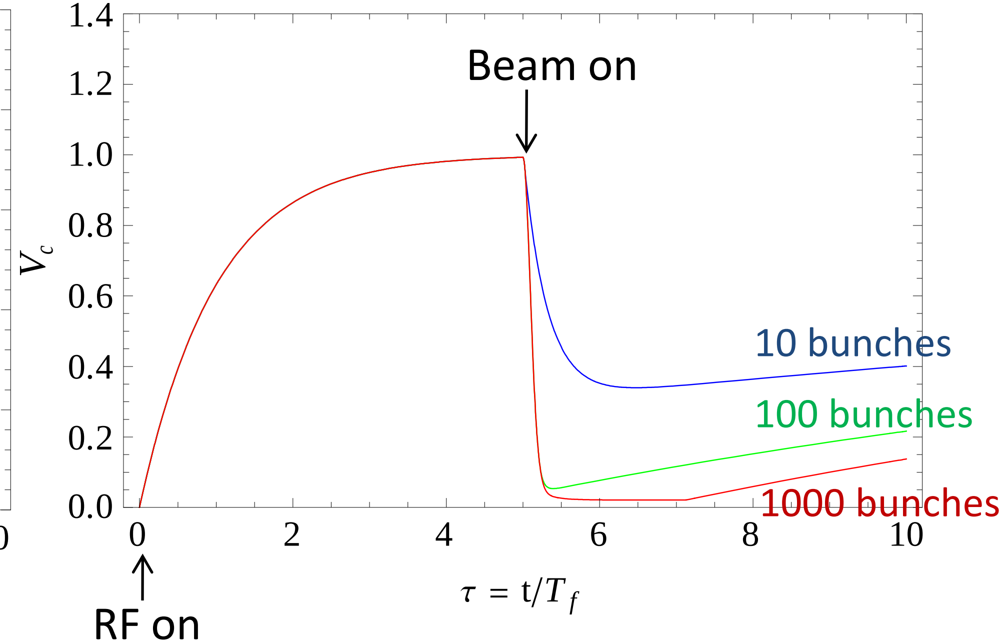
Model Equation

After neglecting beam current, no detuning ($\psi = 0$), and proper normalization (for $\gamma \to 0, \hat{V}_c(\infty) \to 1$)

$$\boxed{\frac{d\hat{V}_c}{d\tau} + [1+\gamma(\tau)]\hat{V}_c = 1}$$

Lots of reflection ($V_R = V_C - 1$)
Heavily under-coupled ($\beta_c << 1$)





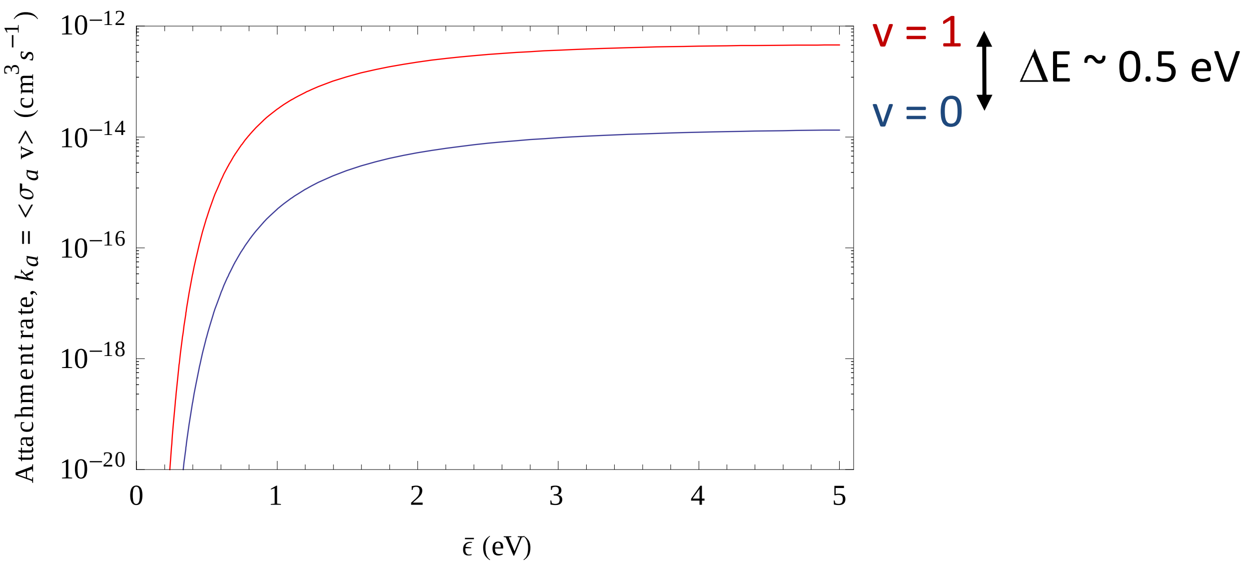
$\gamma \uparrow, T_g \uparrow, k_a \uparrow, n_e \downarrow$

$V_c \downarrow, T_e \downarrow, \beta_r \uparrow, n_e \downarrow$

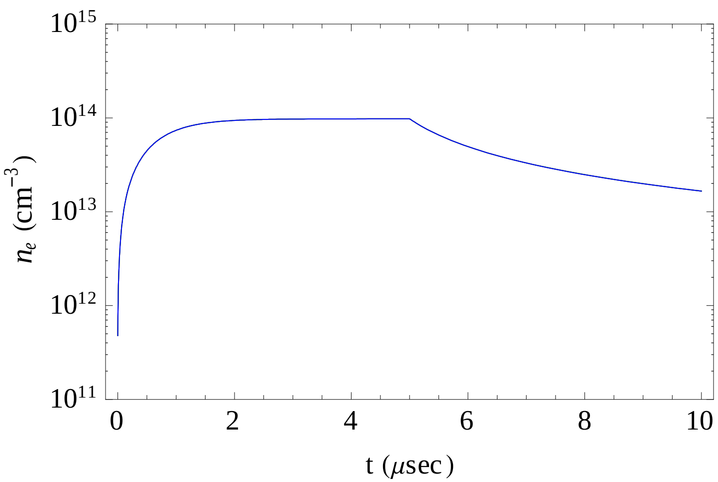
Any Hope ?

$e^- + H_2 \rightarrow H + H^-$

Rate of Dissociative Attachment (DA) increases with the population of vibrationally excited hydrogen (v > 0)

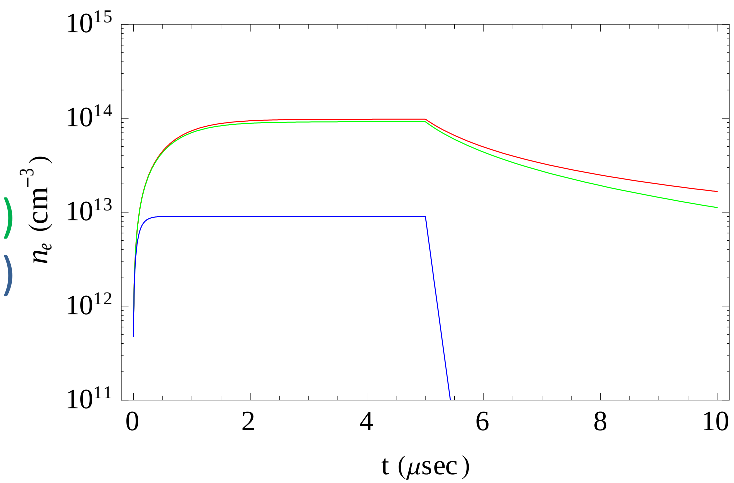


$E_0 / p = 1.0$ V/cm/torr, $\bar{\varepsilon} = 0.28$eV



without DA
with DA (v=0)
with DA (v=1)

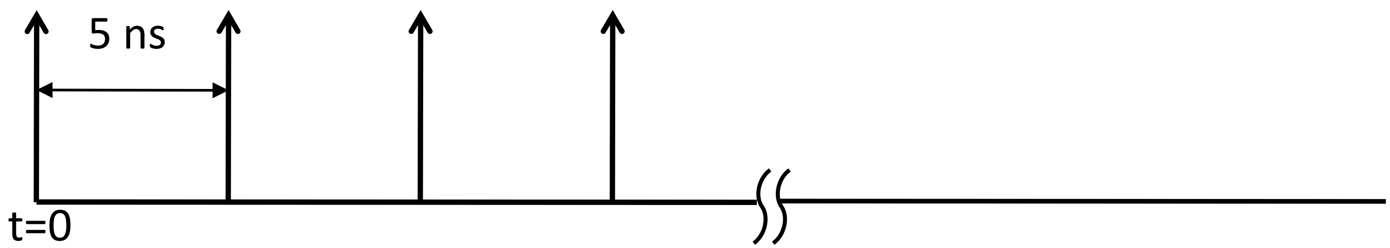
$E_0 / p = 3.9$ V/cm/torr, $\bar{\varepsilon} = 0.73$eV



Time Resolved Optical Emission Spectroscopy

Only if we have enough photons → Photon counting ?

Beam pulse

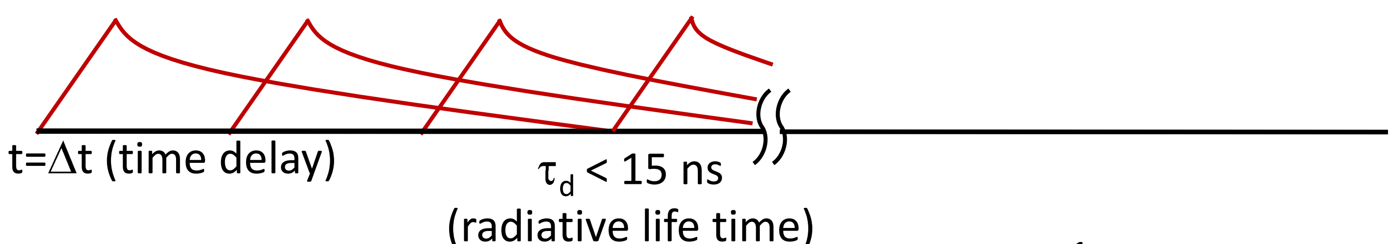


$p + H_2 \rightarrow H_2^+ + e^-$

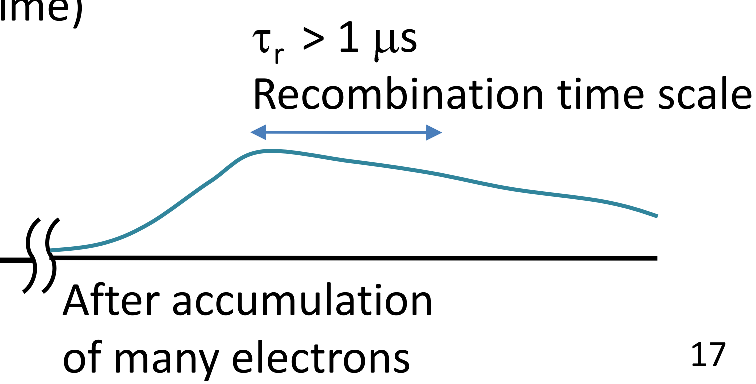
$p + H_2 \rightarrow H_2^* + p$, $H_2^* \rightarrow H_2 + h\nu$: negligible → light comes from electrons !!!

$e^- + H_2 \rightarrow H_2^* + e^-$, $H_2^* \rightarrow H_2 + h\nu$: UV (115 ~ 165 nm, difficult to detect)

$e^- + H_2 \rightarrow H^* + H + e^-$, $H^* \rightarrow H + h\nu$: Hα (656 nm, 2 orders of magnitude smaller than UV)



$e^- + H_2^+ \rightarrow H^*(n>4) + H$, $H^* \rightarrow H + h\nu$: < 434 nm



Conclusions

1. Beam loading from beam itself is estimated to be negligible

2. Beam loading from beam-induced electrons is estimated to be non-negligible
   - Hopefully, recombination, attachment, and diffusion processes are significant than expected
   - Hopefully, adding a small fraction of a dopant gas can help

3. Things in progress
   - Beam commissioning: Matter of time? or Need more manpower?
   - Simulations: Oopic? or LSP?
   - Optical Measurement: Prizm (Grating)? or Filter?
   - Data acquisition (< 1 shot/min):
     - ✓ BPM (or Toroid) → Beam arrival
     - ✓ LabVIEW →BPM (or Toroid), Envelope of Ref and Pickup
     - ✓ Fast scope →Ref, Pickup, PMT1(red), PMT2(blue)

Trigger
@ beam on